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PROBLEMS OF FIRE IN NUCLEAR WARFARE

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I. INTRODUCTION

Mr. Chairman and Members of the Committee:

I welcome the opportunity to discuss briefly with you the possible impact of fire in the unfortunate event of a nuclear attack on the United States. Let me state at the outset that the opinions I express are my own and do not represent any official position of The RAND Corporation where I am employed. Also my remarks are based on a study which has been in progress for only a few weeks and is not yet complete. Furthermore, my field of specialization is nuclear physics and while I have been concerned with the effects of nuclear weapons for a considerable part of the past twelve years, I make no claim to being an expert in the field of fire protection or prevention. I also wish to emphasize that all my remarks are unclassified.

However, as the study has progressed, I have become increasingly convinced that, while fire damage which might be caused by a nuclear attack on the United States could be very serious, it need not be catastrophic in the sense of preventing postwar recovery from rather heavy nuclear attacks.

Furthermore, I am convinced that there are many actions which could be taken before such an attack that would greatly reduce the fire damage inflicted. In addition, if appropriate plans and preparations are made beforehand, many things could be done after the attack to minimize the long term undesirable consequences of the fire damage which might be experienced.

II. GENERAL CONSIDERATIONS

Concern has been expressed[1] that fire from nuclear attacks on various targets might spread far beyond the area of serious damage from blast, thus multiplying the area of destruction many times and that free-running fires would spread through forest and grasslands which would burn over such wide areas that the ecological consequences of soil erosion and floods might make postwar recovery impossible.

The problem of estimating fire damage from hypothetical nuclear wars involves many difficulties and uncertainties. In very general terms, the procedure would involve making assumptions about the enemy choice of time and targets for attack and the number, yield and altitude of burst of weapons delivered on designated ground zeros. These assumptions would be much the same as have been made in previous studies of the effects of blast and fallout, except that one would have to decide whether or not forest and grasslands would constitute a primary target sub-system to which enemy weapons would be assigned or be regarded as a bonus from attacks on other targets such as urban areas or military installations, etc.

To estimate the fire damage, assumptions about a number of additional factors become important. Among these are: meteorological factors such as wind velocity, temperature, relative humidity, visibility, lapse of time since the last precipitation and presence or absence of inversion layers and cloud cover in the target area; fuel characteristics such as types of combustible materials, their surface density, uniformity of distribution and moisture content; topography, geometrical form and degree of builtupness in the target area and finally numbers and distribution of sources of

primary and secondary ignition from thermal and blast effects.

The problem of estimating areas within which initial ignitions would occur for given weapon and target characteristics is relatively straightforward, but estimating the spread of fire from these initial ignitions is much more difficult.

Thus far our study has not progressed to the stage of evaluating fire damage for complete nuclear campaigns, but work has been aimed at understanding the significance and interaction of the various factors outlined above.

One of the most important facts to realize is that in an area as large as the United States, not all of the factors influencing the ignition and spread of fire would be at their worst extremes all over the country during the short period of time required to deliver a nuclear attack. For example, the seasonal periods of worst fire danger are different in different areas of the country and the over-all conditions can vary markedly from year to year which means that careful study of the variations of these conditions for various climatological areas over long periods of time should be evaluated statistically.

For example, Southern California, Nevada and parts of Arizona have experienced extreme drought for the past three years, but large regions in Texas have had such excessive rainfall this year that crops are being severely damaged.

Similarly, the normal periods of maximum fire danger in parts of Maine are July, August and September, while in parts of Florida, Alabama and Mississippi the period from October to March is the most dangerous.

Also in the coastal region of Southern California during the months of July and August when virtually no rain falls, even in normal years, there are almost daily foggy periods which would tend to limit the areas of initial ignition and the degree of fire spread in the event of a nuclear attack during such periods.

One could multiply these examples for each of the factors influencing fire damage showing wide variations in time and place. The implication is clear that an exaggerated, misleading picture will be obtained unless average conditions are considered as well as extremes.

III. FIRE DAMAGE IN URBAN AREAS

Since the only experience with fire damage from actual nuclear attacks resulted from the bombings of Hiroshima and Nagasaki, it is instructive to examine the conditions at the time of these attacks and the resulting fire damage. Table 1 summarizes the bombing data, meteorological conditions and target characteristics at the time of the atomic bomb attacks on Hiroshima and Nagasaki.

It is significant to note that the bomb yield, altitude of burst, meteorological conditions and target fuels were very similar in the two cities at the time of the attacks.

The major differences were the positions of the ground zeros relative to the more densely built-up areas of the cities, their geometrical shapes and their topography.

The fire experience in the two cities is summarized in Table 2.

Examination of Tables 1 and 2 indicates that, despite the favorable burning conditions of clear, dry weather, highly combustable fuels and densely built-up targets, the burned over areas were largely restricted to areas of serious blast damage in both cities and were much less than would be predicted by the primary ignition experiments in the Nevada Tests[4]

The probable reasons for the smaller-than-expected areas of initial ignition and the negligible fire spread are different in the two cities. In Hiroshima, despite the fact that the densely built-up area greatly

Table 1

SIGNIFICANT TARGET PARAMETERS IN THE ATOMIC BOMB ATTACKS ON HIROSHIMA AND NAGASAKI[2,3]

	Hiroshima	Nagasaki
Date	August 6, 1945	August 9, 1945
Time of Day	8:17 a.m.	11:02 a.m.
Weapon Yield	~20 Kilotons	~20 Kilotons
Ground Zero	~1500 ft. N.W. of Center of City	~6000 ft. N. of Center of City
Altitude of Burst	2000 ± 200 ft	1700 - 1750 ft
Visibility	10 - 15 mi.	Unlimited
Cloud Cover	Few High-Altitude Clouds	None (Bright and Clear)
Number of Days Since Last Rainfall	27	10
Climate	Fairly Humid	Fairly Humid
Surface Winds at Time of Detonation	2 1/2 - 4 1/2 mi/hr from S.E.	~3 mi/hr from S.W.
Temperature	Warm, Sunny Summer Day	Warm, Sunny Summer Day
Densely Built-up Area	~6.9 mi^2	~3.8 mi^2
Geometrical Shape of Built-up Area	Broad, fan shape, flat, river delta	> 5 mi. long x 3/4 to 3 mi wide
Topographical Features	Flat, split into 5 islands by 6 river distributaries + wide river valley on north, 221 ft., 1/2 mi long hill on east side. Area mostly 10 ft. above sea level.	Coastal strips on both sides of bay and two river valleys. Hills 500 to 1300 ft. high on sides and dividing valleys.
Builtupness of Damaged Areas	27 to 42 per cent for 94 per cent of central 4 mi^2.	20 to 40 per cent for ~2/3 of ~2 mi^2.
Predominant Structural Materials	Residential Light Wood Frame Bldgs. with Tile Roofs More Reinforced Concrete Structures.	Same but Higher Fraction Industrial Bldgs.

Table 2

FIRE DAMAGE IN HIROSHIMA AND NAGASAKI(2,3)

	Hiroshima	Nagasaki
Type of Fire	Fire Storm; Burned Area Confined Primarily to Area of Initial Ignitions and Serious Blast Damage.	Some Burned Areas Isolated from Main Fire; Some Spread of Fire to Areas Not Seriously Damaged by Blast.
Duration of Fires	Mostly burned out after 10 - 12 hours; Smoldering persisted for 3 or 4 days.	Under Control After 19 hours; finally burned out after 55 - 57 hours.
Time Post Detonation to Peak Fire Intensity.	2 to 3 hours.	Not Same in all Areas; Progressive Fire.
Fire Generated Winds (Max.)	30 - 40 mi/hr at 2 to 3 hrs; Toward Center of Fire.	12 - 36 mi/hr Sporadic, shifting.
Total Area of Serious Structural Damage - Blast and Fire.	4.7 mi^2	1.0 mi^2
Total Area Burned	4.4 mi^2	0.9 mi^2
Area Burned Without Serious Blast Damage	Negligable	~ 0.05 mi^2
Area with Serious Blast Damage that Did Not Burn.	0.3 mi^2	~ 0.1 mi^2
Predicted Maximum Area of Primary Ignitions by Thermal Radiation; Air Burst; 20 KT.	~ 13.5 mi^2 Based on 3 cal/cm^2. 20 KT.	13.5 mi^2 Same

exceeded the burned over area; the fire did not spread appreciably beyond the area of initial ignition because of the rapid development of a "fire storm."

A fire storm is characterized by strong to gale force winds blowing toward the fire everywhere around the fire perimeter and results from the rising column of hot gases over an intense, mass fire drawing in the cool air from the periphery. These winds blow the fire brands into the burning area and tend to cool the unignited fuel outside so that ignition by radiated heat is more difficult, thus limiting fire spread. The conditions which give rise to a fire storm appear to be low natural wind velocity, flat terrain and a uniform distribution of high-surface density, highly combustible fuels which burn rapidly, coalescing individual fires into one burning mass within the fire perimeter.

Such fire storms have been observed in forest fires and were frequently experienced in the mass incendiary air raids in Europe and Japan during World War II. In fact, such fire storms were the most frequent type observed in Japan during mass raids.[5] It was typical in such cases that the fire was mainly confined to the areas initially seeded with incendiary bombs, but within these areas fire destruction was virtually complete.

In Hiroshima, hundreds of fires were burning throughout the area ultimately burned over within ten minutes after the bomb exploded. Each of these spread rapidly to adjacent structures during the first half-hour, by which time the fire storm was well developed. Practically all fire spread had ceased after two hours at which time the fire storm was approaching its peak intensity, with centrally directed winds of 30-40 mi/hr.

In Nagasaki, in spite of the similar yield, altitude of burst and weather conditions, a fire storm did not develop, probably because of the uneven terrain, the irregular layout of the city and the location of ground zero in a long relatively narrow river valley north of the center of the city. Here, such spread of the fire beyond the area of initial ignition as was observed, was to the southeast against the wind direction at the time of the explosion. Because the rate of spread was slower, the fire burned longer. Here also, the combination of terrain, city layout, position of ground zero and wind direction limited the spread of fire primarily to areas seriously damaged by blast.

The fact that the areas of primary ignition from thermal radiation were significantly smaller than the area predicted for dry, combustible, light fuels (newspaper, etc.) in both cities was probably due to a number of factors. In the first place, the ignition energies measured at the Nevada Tests were made under conditions of very low humidity typical of the desert. Since Hiroshima and Nagasaki are both seacoast cities cut by numerous bays and rivers, the relative humidity was probably considerably higher than in the Nevada desert, thus increasing the ignition energies markedly. Also not all potential sources ignite because many are shadowed from the thermal radiation and of those which do ignite, many are not close enough to heavier fuels to ignite them and quickly burn out or are blown out by the blast wind. The fact that initial fires in both cities were confined to areas of substantial blast damage suggests that most of them, at least at the outer limits of these areas, were the result of secondary ignitions caused by blast damage. This was born out by the testimony of survivors.

In Nagasaki, many areas were protected from both blast and thermal radiation by being in the shadows of hills and ridges and this, coupled with the long narrow shape of the built-up area in the valley around ground zero and the much lower builtupness at the north end of the valley, limited both the blast and fire damage even more than the development of the fire storm in Hiroshima.

All this does not deny that under exceptional conditions of high wind, very low fuel moisture and a high degree of builtupness fire spread from areas of initial ignition can occur. For example, in the incendiary raid on Tokyo of March 9, 1945, an area of 8 square miles of the most highly combustible area of the city was seeded by bombers. The fire spread over 16 mi^2 in 6 hours, completely destroying it.[6] Fires that spread rapidly along a front driven by high natural winds are called conflagrations. It is important to note however that fire spread of this magnitude (factor of 2) was a relatively uncommon experience during the World War II incendiary raids in Europe and Japan. The most frequent experience was that the area completely destroyed by fire was equal to or less than the areas initially seeded with bombs.

Since weapons today are likely to be in the megaton class, the absolute areas of fire damage in Hiroshima and Nagasaki are not of great significance, but the fact that many situations are likely to be encountered in different targets that would reduce the areas destroyed by factors of from 3 to 13 over what would be predicted by the most pessimistic assumptions, is of great importance for realistic evaluations of the effects of thermonuclear attacks.

For megaton weapons, the thermal energy is released over a longer time than for kiloton weapons so that fuels that would require 2-3 cal/cm^2 to be ignited by a 20-kiloton explosion would require 4 to 5 cal/cm^2 for one of 10 megatons. Thus under very dry conditions and with unlimited visibility, an air-burst 1-megaton weapon could produce primary ignitions out to a distance of 10-11 miles and a 10 megaton one out to 25 miles or over areas of 380 and 2000 mi^2 respectively.[7]

However, if these weapons were surface burst under more normal conditions of fuel moisture and atmospheric visibility, these areas could be reduced to less than 200 and 1600 mi^2 respectively. Under conditions of recent rain, irregular target geometry, hilly terrain and poor visibility, the maximum estimates could be reduced by a factor of 10 or more.

It is important to point out that, if an enemy chooses to surface burst his weapons in order to cover large areas with high levels of fallout radiation, he cannot at the same time achieve the maximum area of primary ignition that would result from the same weapons, air burst, because part of the thermal energy is absorbed in the ground and in debris from the crater which mixes with the fire ball. Also the area of shadows cast by hills, buildings, etc., would be greater so that fewer potential sources of primary ignition would be exposed to direct thermal radiation.[8]

IV. IMPLICATIONS OF MASS FIRE FOR FIRE PROTECTION AND CIVIL DEFENSE ORGANIZATIONS

One of the first conclusions to be drawn from the World War II experience with mass urban fires is that, in the areas severely damaged by blast, fire fighting is virtually impossible. In the first place, a large percentage of unsheltered fire-fighting personnel in such areas would be killed or injured and their equipment destroyed by the blast. Even if such facilities were protected by blast shelters, the debris in the streets would make it impossible to get to the fires. Furthermore, the large numbers of fires and their rapid development in a matter of minutes would completely overwhelm the normal capacity of the fire-fighting services and the heat would rapidly reach such high levels that personnel in the open could not live. Furthermore, the many breaks in the water system would reduce the available water to negligible amounts in a short time.

Any additional fire-fighting equipment and personnel that might be provided for emergency use following a thermonuclear attack should be located well outside blast damage radii, peripheral to likely targets and provided either with water supplies independent of the city system or ample fire-fighting chemicals. Their function would be to fight the spread of fire at the periphery of blast damage.

Similar considerations apply to emergency rescue, first aid and medical teams and to all sorts of emergency supplies of food, medicines and portable emergency hospitals. Also all such facilities should be as highly dispersed as is economically feasible and practical.

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Another serious problem is that for surface burst weapons, deposition of fallout would be taking place during just the period when such emergency services are most urgently needed. Such emergency units should be provided with fallout shelters and radiation monitoring equipment. Also the feasibility of shielded vehicles designed for the specific tasks of such units should be investigated.

The mass fire problem has another important consequence for shelter programs. Any shelter designed to withstand appreciable blast pressures or located in an area where mass fire is probable, should be designed so that it can be completely sealed off from the outside air and a recirculating air purification and cooling system capable of operating for the duration of the fire should be provided. The reason is that during an intense mass fire, the air reaches high temperatures and becomes contaminated with carbon monoxide and dioxide as well as heavy smoke so that it would not provide a viable atmosphere for the shelter occupants. Many occupants of bomb shelters were found dead after the great Hamburg fire storm, apparently killed by asphyxiation, carbon monoxide poisoning or heat, who were otherwise uninjured and could have survived if the shelters had not been dependent on the outside air supply for ventilation.[9] It also goes without saying that such shelters should be adequately insulated from conducted heat, i.e., several feet underground.

A number of precautionary measures could greatly reduce the probability of primary ignitions in urban areas. Since combustible trash, such as scrap paper, excelsior and punky or rotten wood, are the fuels most easily ignited by thermal radiation, rigorously enforced regulations requiring that such trash be kept picked up and stored in tightly covered

metal containers could greatly reduce the chance of primary fires outside the area of secondary ignitions resulting from blast damage. Also the proper care of exposed wood surfaces by painting is important. These procedures have the added merit of being good fire prevention practice under normal conditions as well as improving the general appearance of a city. Surveys of potential sources of primary ignitions in typical U. S. cities have shown that the numbers of such sources can be as low as 1100 to 1600 per mi^2 in well kept residential areas, whereas there can be as many as 11,000 to 15,000 per mi^2 in slum residential and wholesale warehouse areas at thermal energies of 5 - 8 cal/cm^2.[10]

Another precautionary measure that was tried during World War II was to clear firebreaks in cities. The net experience in Hiroshima and Nagasaki and in other Japanese cities that suffered mass incendiary raids was that firebreaks inside areas where primary and secondary fires were densely ignited over large areas had little effect on the development of mass fire storms or conflagrations, but in some cases both natural and artificial firebreaks of sufficient width helped to limit fire spread over small portions of the fire perimeter.[11]

One of the chief factors influencing fire spread is the degree of builtupness or the ratio of roof area to ground area. A survey of eleven Japanese cities indicated that for residential areas with 45 per cent builtupness, 72 per cent of the exposed areas burned. With 30.6 per cent builtupness, 46 per cent burned and with 15.5 per cent builtupness, 20 per cent burned.[12]

While it would not be economically feasible to decrease the builtupness in areas already built, it might be possible in many cases to regulate the

maximum builtupness in new urban areas being developed. In this connection, the average U. S. city, particularly in residential areas, is less built-up and less combustible than Japanese cities, so that fire damage here should be a smaller fraction of the exposed area.

V. FOREST FIRES IN THERMONUCLEAR WAR

The problem of estimating the total area of forest and grassland that might be burned over in a thermonuclear attack on the U.S. and the effect of its long-term consequences on post-attack recovery is fraught with many uncertainties. Forest and brush fires could be ignited by spread from fires started in urban and military targets or by the overlap of the area of primary ignition from weapon explosions on forested areas. Also in any large attack, there would probably be a number of gross bombing errors which could ignite wildland areas primarily.

It is even conceivable that an enemy might choose to allocate weapons specifically to the task of starting wildland fires, but in view of the importance to him of reducing our retaliatory capability to a minimum, this appears rather unlikely. It is true that the Japanese made a feeble, unsuccessful attempt to do this in World War II with balloon-delivered incendiaries,[13] but this was the only means they could devise to carry any form of attack to the U.S. heartland and probably was never expected to accomplish more than a nuisance value.

A little over one-third the area of continental U.S. and Hawaii or about one million mi^2 is forest, brush and grassland. Alaska contributes an additional 416,000 mi^2.[14] A little over one-fourth of this area is not utilized to grow saw-timber or other forest products, but serves to protect watershead areas from soil erosion, to reduce flood danger and to replenish ground water supplies.

In order to have some yardstick by which to measure the impact of possible forest fire damage from a nuclear attack, it is of interest to look briefly at forest fire experience in the past.

It is important to understand that the cooperative effort of government and private organizations to reduce the annual fire damage to our forests began slowly during the first decade of this century and was making real progress by the late thirties. By 1959, 94.7 per cent of the forestlands in the continental U.S. had organized fire protection. The effect of this was to reduce the average annual burned forest area from 65,000 mi^2 for the eleven years from 1926 to 1936 to 5,340 mi^2 for the three years from 1957 to 1959.[15] Table 3 summarizes the forest fire experience in the continental U.S. for the period 1926 to 1959.

The eleven-year period from 1926-36 is of interest because there is no obvious trend of decreasing annual burned areas because of improved fire protection such as are shown from 1937 to the present. The range of fluctuation of annual burned areas is probably mainly due to the effects of variation in weather on burning conditions from year to year. This also applies to the fluctuation in the annual number of forest fires. For example, the lowest annual burned area of 38,000 mi^2 was in 1926, while each of the years, 1930 and 1931, accounted for 81,000 mi^2. The range was 42 per cent above the average and 25 per cent below. For the annual number of fires, 1926 was the lowest with nearly 92,000 and 1936 the worst with over 226,000, the range being 40 per cent above and 43 per cent below average.

Similarly, the average area burned per fire was 261 acres or about 0.4 mi^2 and the range was from 191 acres in 1936 to 343 acres in 1929 or 27 per cent below average and 31 per cent above.

The above figures suggest that for a nationwide nuclear attack of given magnitude on specified targets, variations in the total forest area

Table 3

FOREST AREA BURNED ANNUALLY AND NUMBERS OF FIRES IN CONTINENTAL U.S.[16]

Period	Average Area Burned mi^2	Maximum Area Burned mi^2	Minimum Area Burned mi^2	Average Number of Fires	Maximum Number of Fires	Minimum Number of Fires
1926-36	65,000	81,000	38,000	161,420	226,285	91,793
1937-47	39,900	52,800	25,900	188,438	232,229	124,728
1948-58	16,000	25,900	5,125	157,268	208,400	83,391
1957-59	5,340	5,570	5,125	95,241	104,422	83,391

burned, because of variation in annual fire hazards, could be expected to be about a factor of two from the best to the worst years.

VI. CATASTROPHIC FOREST FIRES

Probably one of the principal reasons why some people have expressed the opinion that a very large fraction of our forested areas would be burned in the event of a nuclear attack is that they are familiar, either through direct experience or study, with the destruction resulting from a number of great catastrophic forest fires in the past. They envision large factors of fire spread from each of a large number of megaton weapons detonated, in all parts of the U.S., under the worst burning conditions possible.

The term, "catastrophic forest fire," is usually reserved for fires which spread over areas of 150 mi^2 or more causing great property damage in terms of timber and buildings destroyed and frequently resulting in loss of lives. Since 1825 there have been 12 great catastrophic forest fires. The greatest of these burned over an area of 5900 mi^2 in Northern Michigan and Wisconsin in October 1871. Many towns and farms were destroyed and 1638 lives were lost. A large part of the burned area was valuable virgin forest.[17]

In the period from 1825 to 1910 there were 8 great forest fires resulting in burned-over areas varying from 250 mi^2 to 5900 mi^2 each. Since 1910 there have been four great fires which burned over from 156 mi^2 to 469 mi^2 per fire. The most recent of these were the fires in Maine and New Hampshire in October 1957 and the Malvern Hill fire in Florida in 1956. The former burned over 375 mi^2, destroyed much property in Bar Harbor and took 16 lives.

These great fires are truly terrifying in their intensity, rate of spread and the violence of the fire-generated winds which blow down large trees in advance of the flames and spread flaming brands to spot new fires

5 to 6 miles ahead of the fire front.

The Tillamook Fire[18] in Oregon during August 1933, burned 486 mi^2 of virgin Douglas Fir. The speed with which a forest fire can spread in heavy fuels under the most hazardous conditions is well illustrated by this fire. From August 14 at 1:00 p.m. until the early morning of August 24, the fire had burned about 63 mi^2 and it appeared that it might be brought under control soon. Thus, for over 10 days it had burned at an average rate of about 6 mi^2 a day. On the 24th, the humidity droped rapidly to 26 per cent and hot gale-force winds from the east sprang up. During the next 20 hours of August 24 and 25 the fire burned over an additional 420 mi^2, or at a rate of 21 mi^2 per hour along a 15-mile front. The fire was stopped only by the fact that the wind ceased and a thick, wet blanket of fog drifted in from the ocean.

It is important to realize, however, that very special conditions are necessary to make such great conflagrations possible. First, the stage is usually set for such fires by an abnormally dry year or possibly two or three such years in succession. Then a hot period of several weeks without rain, immediately preceding the fire, followed by hot, dry winds approaching gale strength, which drive the relative humidity down to 20 or 30 per cent, and a large area of fairly dense forest fuel complete the setting for catastrophy. All that is needed is a source of ignition to start a holocaust. Fortunately, these conditions are met rather infrequently and not over the whole country at any one time. During the period from 1825 to 1956 the average interval of time between catastrophic forest fires was about 11 years. Only once were such fires experienced on successive years, the Yacolt

fire in the state of Washington in 1902, being followed by the Adirondack fires in New York in 1903. The next shortest interval was 7 years and 5 intervals of 13 years or longer between such fire disasters occurred.

A number of factors have served to reduce the areas burned in catastrophic fires, such as the reduction in large unbroken areas of virgin forest brought about by the clearing of much land for agriculture and other uses as the country becomes settled, better lumbering practices and organized fire protection services.

Another important thing to remember is that most of these great fires were not stopped by fire fighting, but by natural barriers such as lakes, rivers and deserts, or by a change in weather conditions such as the onset of rain or fog or changes in the winds.

If such fires could occur frequently, the white man on coming to the New World would not have found over half its area covered with vast unbroken areas of virgin forests. A frequent cause of forest fires throughout the U.S. is lightning, or 1,000 to 2,000 fires annually are caused by lightning.[19] More than two-thirds of the fires in the Rocky Mountain states and one-third in the Pacific Coast states are ignited in this manner.

Since similar numbers of fires must have started in the forests prior to the coming of the Europeans, most of them must have burned out by themselves without turning into great conflagrations. There are evidences of some large fires which can be read in the tree rings of the redwoods that have been growing since before the time of Christ.[20] Also, many of the stands of southern pine and Douglas Fir are thought to be the result of fires which favored these more fire-resistant types. The conclusion appears inescapable that the large free-running catastrophic forest fire would occur very infrequently as the result of the detonation of a nuclear weapon.

VII. PRIMARY IGNITIONS IN FOREST FUELS BY MEGATON WEAPONS

While many of the factors that determine the distances to which primary fires could be started in forest fuels by megaton explosions are similar to those discussed for urban-area fuels, there are some important differences. In the first place, the thermal energy required to ignite the most susceptible dry forest fuels is greater than for dry urban-area trash. Dry, rotted wood or punk appears to be the most easily ignited forest fuel, 4 cal/cm^2 being required for a 20-kiloton weapon and 9 cal/cm^2 for a 10-megaton weapon. Fine, dry grasses require 5 and 10 cal/cm^2; dry leaves, 6 and 12 cal/cm^2; and dry pine needles from 6 to 8 cal/cm^2 for 20 kilotons and 14 to 18 cal/cm^2 for 10 megatons.[21]

A second difference is that sources of secondary ignition resulting from blast damage would be very few in forested areas compared with urban areas. Also, in areas of very dense forest fuels which correspond to densely built-up urban areas, the forest canopy would shade the more easily ignited fuels on the forest floor from thermal radiation to a greater degree than structures in urban areas.

It is significant that in Nagasaki where the hillsides of the narrow valley were wooded and free of buildings, there was no evidence that the trees and brush were ignited by the direct thermal radiation from the explosion. In some areas trees were scorched, but no spreading brush fires resulted. Also, there was no general spreading of fires from burning structures to the wooded hillsides, although a few small areas of brush and grass immediately contiguous to hot fires in buildings were blackened.[22]

The Forest Service of the U.S. Department of Agriculture has published

the results of a study[23] designed to aid in estimating the "probable burn-out areas" that might result from airburst nuclear weapons of 1, 3 and 10 megatons. These burn-out areas are displayed in tabular form for 475 U.S. regions, supposedly characterized by their climatology, natural fire barriers and areas covered by forest and rangeland, and for each month of the year. For the regions and 3 to 5-month periods of minimum fire hazard, the entries apparently correspond to the areas of primary ignition by thermal radiation for the various bomb yields. For other regions and periods of greater fire hazard, a degree of fire spread is allowed for ranging up to a factor of 41 for 1 megaton and a factor of 12 for 10 megatons in the worst regions and the worst months.

Table 4 shows the minimum areas listed and the thermal energies to which they correspond for airburst weapons and unlimited visibility. The maximum areas of spread listed are also shown. The areas were apparently chosen as those which would result if the prevailing level of fire danger approximates the average peak fire danger attained two to four times during the month.

These estimates of fire spread, while taking into account variations in fire hazard from month to month and from region to region, in my opinion, still overestimate the burned areas, because they represent the 2 to 4 days during each month when the average peak fire danger is greatest. They correspond to conditions which would be experienced on the average only 10 per cent of the time.

Also the estimates showing the largest fire spread give greater burned areas than have ever been observed in the most catastrophic forest fires of the past. When one considers that the greatest of these burned

Table 4

FIRE SPREAD FROM THERMONUCLEAR WEAPONS

Bomb Yield in Megatons	Minimum Area of Spread in mi^2	Thermal Energy in cal/cm^2 at Limit of Minimum Area	Maximum Area of Spread in mi^2
1	200	10	8280
3	380	12	8630
10	800	18-20	9940

over 5900 mi^2, estimates of 8000 to 9000 mi^2 under conditions where the forest cover is far less continuous than it was in 1871 in Northern Michigan and Wisconsin, appear very unlikely.

It is also important to understand that the great fires during the 1800's were not the result of spread from single ignition points, but really were many independent fires which coalesced under extremely hazardous fire conditions. During these periods it was customary to pay little attention to forest fires if they did not endanger settled communities. Fires were burning in the debris resulting from lumbering and land-clearing operations most of the time. Forests were regarded as an unexhaustible resource, or in many cases, as a nuisance. Probably the largest areas that would burn over now would be more characteristic of the catastrophic fires experienced since 1910, or less than 500 mi^2, and these would occur with a very low probability.

Dr. Mitchell has discussed the ecological problems that can result from forest fires and the various methods that are available to deal with them during postwar recovery. In this connection, if one takes the lower estimates of burned areas shown in Table 4 as being more reasonable than assuming large factors of spread, 405 one-megaton bombs, 213 three-megaton bombs, or 101 ten megatons aimed specifically at the forests would do damage comparable to that experienced in each of the years 1930 and 1931. Furthermore, since the ecological consequences of forest fires extend over many years, twice as many bombs as mentioned above would be comparable in ecological consequences to the combined effects of the 1930 and 1931 forest fire experience. While such forest damage as was experienced in 1930 and 1931 was undoubtedly serious, it is clear that recovery from such damage and

the damage experienced by fire year after year probably would not be sufficient to prevent postwar recovery.

Another point of interest is that in saw timber stands, which have been devastated by fire, much of the lumber can be salvaged during a period of years following the fire and before insect damage destroys its usefulness for lumber. For example, between 1933 and 1952, 8-10 billion board feet of lumber were salvaged from the Tillamook burn.[24] Since much lumber would be needed for postwar reconstruction, it would be important to plan for such salvage operations. In addition, this procedure improves conditions for the recovery of the forest and makes future fire damage less probable.

VIII. PREVENTIVE AND CORRECTIVE MEASURES FOR FOREST PROTECTION

There are a number of things that could be done during the years preceding a nuclear attack which could reduce the fire damage to forestland in the event of such an attack.

First the practice of good silviculture, which keeps the forests free of dead snags and floor clutter, would reduce the probability of primary ignitions from thermal radiation and reduce the intensity of any fires occuring. This, in turn, reduces the probability of crown fires, which are the most damaging to mature trees.

Increasing and improving the care of fire breaks would help limit the spread of fire and increasing the numbers of access roads would make fire fighting easier.

Improving and expanding the fire protection services would reduce peacetime forest fire damage which at the same time would reduce the danger of fire during nuclear attack. Forest areas which have been severely burned become more susceptible to fire because the cover that grows during the first few years after a fire is more easily ignited and the dead snags left from previous fires burn more readily. For example, most of the Tillamook burn area burned over again in 1939 and in 1945, and a smaller fire covering 38,000 acres burned in 1951.

Research and development aimed at improvement of methods of fighting forest fires, particularly in the presence of fallout, might lead to a real capability to combat fires following a nuclear attack. The use of aircraft to fight forest fires has increased during recent years and further developments of these techniques could be of great importance.

The development of more tree farms and improved methods of reseeding or replanting burned forest areas could also be of great service in repairing forest damage during the recovery period following a nuclear attack.

Most of these measures would greatly reduce our peacetime forest fire damage and would not be wasted in the event, as we all fervently hope, that no nuclear war is experienced.

IX. CONCLUSIONS

Fire damage to urban and forested areas from a nuclear attack is frequently estimated by taking the most pessimistic values for all factors involved. This leads to gross overestimates of the damage likely to be experienced. By making the situation appear hopeless, such estimates do a great disservice by preventing actions which could do much to reduce the damage from a nuclear attack and help speed recovery during the postwar period.

Preliminary study indicates that fire damage to urban areas is likely to be confined largely to areas seriously damaged by blast. In relatively infrequent weather situations, fire may spread beyond the areas of blast damage, but even in these cases, increase in damage area due to fire spread is unlikely to exceed a factor of two.

Estimates that conclude that fire would destroy the greater part of our forest and rangelands are probably very erroneous, because the enemy would use his weapons to better advantage by assigning them to military or urban targets and spread of fire from such targets to forest areas is unlikely to occur for the major portion of these targets.

Many measures can be taken before attack that would reduce the fire damage, if an attack should occur, and also aid in post-attack recovery. Such measures require study, research and development. Those that show real merit should be incorporated into civil defense systems.

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